AD-A026 099

AMMRC TR 76-16

AD A026 099

AUSTENITE STABILITY AND TENSILE PROPERTIES OF WARM-EXTRUDED TRIP STEELS

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May 1976

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AMMRC TR 76-16	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AUSTENITE STABILITY AND TENSILE PROPERTIES OF WARM-EXTRUDED TRIP STEELS		5. TYPE OF REPORT & PERIOD COVERED Final Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Morris Azrin, Gregory B. Olson, and Roger A. Gagne		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Army Materials and Mechanics Research Center Watertown, Massachusetts 02172 DRXMR-EM		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 1T162105AH84 AMCMS Code: 612105.11.H8400 Agency Accession: DA OE4819
11. CONTROLLING OFFICE NAME AND ADDRESS Army Material Development and Readiness Command Alexandria, Virginia 22304		12. REPORT DATE May 1976 13. NUMBER OF PAGES 8
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

TRIP steels	High strength steels
Thermomechanical treatment	Martensite
	Austenite
Extrusion	Precipitation heat treatment

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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ABSTRACT

High austenite stability resulting from a variation of working temperatures during warm extrusion caused insufficient work hardening and a loss of ductility in warm-extruded TRIP steel. The austenite stability could be adjusted, however, by a tempering treatment to remove some carbon from solid solution, giving tensile properties equivalent or superior to those obtained by warm rolling. Difficulties in alloy composition control or temperature control during processing of TRIP steels can thus be compensated by a simple final heat treatment.

INTRODUCTION

TRIP steels appear to offer the highest combination of strength, ductility, and fracture toughness of any known alloy.[1,2] The high ductility and fracture toughness of these metastable austenitic alloys are a result of a strain-induced martensitic transformation during service, while the high yield strength levels are usually obtained from the prior thermomechanical treatment. The highest strength levels are obtained by a reduction of 80% by rolling at temperatures from 700 to 1000 F. These high rolling reductions at such moderate temperatures impose severe restrictions on the fabrication of these materials. For certain applications it may be desirable to use alternative processing techniques. Thermomechanical treatment by warm extrusion appears to offer some potential advantages over warm rolling, particularly for applications requiring material in bar or rod form.

The warm extrusion of TRIP steels has been investigated and reported in detail in Reference 3. A significant result of this study was that, unlike the nearly isothermal conditions encountered in sequential warm rolling, substantial temperature increases on the order of 300 F occurred during warm extrusion. Accordingly, the initial billet temperature was adjusted to obtain a final temperature of approximately 850 F, corresponding to the warm-rolling temperature known to give the best mechanical properties for the alloy composition studied.

It may be anticipated that a varying temperature during thermomechanical processing would have a serious effect on the final mechanical properties of a TRIP steel. It is well established that the austenite stability with respect to martensitic transformation in these alloys is sensitive to the temperature of warm working,[4,5] higher working temperatures usually resulting in lower stability. This effect is attributed to carbide precipitation (or pre-precipitation effects) concurrent with the plastic deformation which results in a decrease of carbon in solid solution. Austenite stability has a profound influence on the mechanical properties of a TRIP steel. Too high a stability results in insufficient strain-induced transformation in service and hence a loss of ductility and toughness. Too low a stability can cause a drastic reduction in yield strength due to the premature plastic flow associated with a stress-assisted martensitic transformation. Examined here are the tensile properties of the warm-extruded TRIP steels, with particular regard to the effect of the increasing warm-working temperature on the austenite stability.

1. ZACKAY, V. F., PARKER, E. R., FAHR, D., and BUSCH, R. *The Enhancement of Ductility in High-Strength Steels.* Trans. ASM, v. 60, 1967, p. 252-259.
2. ANTOLOVICH, S. D., and SINGH, B. *On the Toughness Increment Associated with the Austenite to Martensite Phase Transformation in TRIP Steels.* Met. Trans., v. 2, 1971, p. 2135-2141.
3. GAGNE, R. A., AZRIN, M., and DOUGLAS, J. R. *Warm Extrusion of TRIP Steels.* Army Materials and Mechanics Research Center, AMMRC TR 76-2, January 1976.
4. GERBERICH, W. W., THOMAS, G., PARKER, E. R., and ZACKAY, V. F. *Metastable Austenites: Decomposition and Strength.* University of California, Berkeley, UCRL-20308, August 1970.
5. MAKSIMOVA, O. P., UTEVSKIY, L. M., ZAMBRZHITSKIY, V. N., NOGAYEV, M. A., and MOSKVICHEV, I. F. *Development of Martensitic Transformation During Deformation, and the Mechanical Properties of TRIP Steels.* Physics of Metals and Metallography, v. 34, no. 5, 1972, p. 165-176. Translation of Fiz. Metal. Metalloved, v. 34, no. 5, 1972, p. 1075-1087.

MATERIAL AND PROCEDURES

The material preparation is described in Reference 3. Nominal composition of the alloy is Fe-9Cr-8Ni-4Mo-2Si-2Mn-0.3C. Both air and vacuum melts were used (Table 1). Ingots were homogenized at 2300 F for 6 hours, press forged to 3-3/8-inch diameter at 2100 F, and machined to 3-1/8-inch-diameter billets. The billets were extruded to 1.25-inch diameter at 2100 F, solution treated at 2250 F for 1 hour and water quenched. The solution-treated billets were then warm extruded to 40%, 60%, or 80% reductions of area. Because of the temperature rises during extrusion, the initial billet temperatures were adjusted to produce a final extrusion temperature of approximately 850 F. In order that the initial deformation temperature should always remain above M_d (maximum temperature for formation of strain-induced martensite) the 80% reduction was performed in two steps, 60% followed by 50%. Temperature changes during extrusion are listed in Table 2.

Round tension specimens of 0.200-inch diameter and 1.25-inch reduced section were machined from the extruded rods. Room temperature uniaxial tensile properties were measured using a 20,000-lb Instron tension testing machine at a crosshead speed of 0.050-inch per minute. Elongations were measured with a one-inch gage length extensometer.

RESULTS AND DISCUSSION

Preliminary tension tests of the warm-extruded material gave 0.2% offset yield strength values of 145, 211, and 244 ksi for the extrusion reductions of 40%, 60%, and 80%, respectively. These are equivalent to the strength levels

Table 1. CHEMICAL COMPOSITION (Wt%)

Melt	C	Mn	Si	Ni	Cr	Mo	P	S	Al	N	O*	H*
Air	0.25	2.16	2.11	7.73	8.86	4.08	0.003	0.010	0.05	0.060	25	8.5
Air	.26	2.18	2.02	6.81	8.90	4.09	.003	.010	.06	.044	63	3.9
Air	.27	2.17	2.14	7.75	8.87	4.04	.003	.010	.04	.065	47	7.3
Air	.27	2.16	1.93	7.79	8.96	4.06	.003	.010	.06	.054	49	3.7
Vacuum	.33	2.25	2.06	7.56	9.06	3.97	.003	.009	.08	.004	2.2	6.0
Vacuum	.33	2.32	1.77	7.71	8.98	4.14	.002	.009	.10	.003	0.3	5.5
Vacuum	.33	2.27	2.03	7.68	8.90	3.96	.003	.009	.09	.003	1.1	5.8

*Parts per million

Table 2. WARM EXTRUSION TEMPERATURES

Reduction (%)	Temperature, deg F Initial	Final	ΔT
40	700	820-860	120-160
60	500	800-850	300-350
50*	400	790-850	390-450

*Step 2 of 80% cumulative reduction

obtained by warm-rolling alloys of this composition. The reductions of area measured in the tension tests were also comparable to those of warm-rolled material. However, the total elongations* and overall work-hardening characteristics were generally less than those of warm-rolled material, particularly in the case of the 80% worked material where a Lüders band formed but did not travel the gage length of the specimen before fracture. This resulted in a total elongation in 1-inch of only 12% compared to values of about 40% obtained from similar warm-rolled material. Such behavior is characteristic of an insufficient rate of strain-induced martensitic transformation resulting from too high an austenite stability. A test of the material in the solution-treated condition gave the properties expected for this alloy composition, confirming that the high austenite stability is not due to a variation in the basic composition but a result of the thermomechanical processing.

Since the alloy composition used in this study was designed to give an optimum austenite stability after warm working at 850 F, it is not surprising that the warm extrusion process used here, in which the *average* working temperature was below 850 F, gave rise to too high an austenite stability. However, it was found that the austenite stability can be suitably modified (decreased) by a simple heat treatment after the warm extrusion. Assuming that the high austenite stability is the consequence of insufficient carbide precipitation at the lower average working temperature, it can be expected that the correct level of stability could be obtained by a tempering treatment to enhance carbide precipitation and thus remove more carbon from solid solution. However, adjustment of stability in this manner could lead to a trade-off in ductility (reduction of area) if such a thermal treatment, without concurrent plastic deformation, leads to excessive grain-boundary carbide precipitation and an intergranular fracture mode. To test the feasibility of such an approach to austenite stability adjustment, tension specimens of the warm-extruded material were tempered for 1 hour at temperatures of 1000, 1100, and 1150 F.

The tension test results are listed in Table 3, and the individual engineering stress-strain curves of the 40%, 60%, and 80% worked materials are plotted in Figure 1. Included in Table 3 are Young's modulus values taken from the initial slopes of the stress-strain curves. The values indicate a lower modulus of the worked material relative to the solutionized condition, presumably due to internal strain energy and a high dislocation density.[6] The overall tensile properties suggest little difference between the air- and vacuum-melted materials.

The stress-strain curves of the warm-extruded material in Figure 1 show that although the total elongation of the 60% worked material was quite high, that of the 40% and 80% worked materials was relatively low. The curves for the tempered material show that the reduced austenite stability, brought about by tempering, increases the overall work-hardening rates and results in a general increase in the total elongation. Somewhat surprisingly, the results in Table 3 indicate that tempering at 1000 and 1100 F also increases the reduction of area. Carbide precipitation does not seem to cause embrittlement until the tempering of the 80% worked material at 1150 F where a drastic decrease in reduction of area is found. Figure 1c shows overaging at 1150 F not only causes embrittlement but gives too low an austenite stability resulting in a lower yield strength from a premature stress-assisted transformation. The influence of tempering temperature on the

*Obtained from 1-inch marks on the specimen (length/diameter = 5 instead of the standard ratio of 4).

6. ZENER, C. *Relation Between Residual Strain Energy and Elastic Moduli.* Acta Crystallographica, v. 2, 1949, p. 163-166.

Table 3. MECHANICAL PROPERTIES

Condition		Melt	Y.S. 0.2% (ksi)	T.S. (ksi)	Elon.* (%)	R.A. (%)	E (10^6 psi)
Solutionized	2000 F - 1 h Water Quench	Vacuum	45.3	93.2	56	40.2	26.7
40% Warm Extruded	As extruded	Air	144.5	159.1	13	25.6	22.9
	1000 F - 1 h	Vacuum	135.0	182.5	58	57.4	23.2
	1100 F - 1 h	Vacuum	135.7	198.6	41	33.7	24.4
60% Warm Extruded	As extruded	Air	211.4	211.8	37	35.3	24.3
	1000 F - 1 h	Vacuum	207.4	207.4	36	52.3	23.4
	1100 F - 1 h	Vacuum	206.9	227.5	40	38.1	21.8
	1100 F - 1 h	Air	222.9	240.7	41	52.3	23.4
80% Warm Extruded	As extruded	Air	244.2	260.5	12	47.5	23.7
	1000 F - 1 h	Vacuum	261.0	274.4	25	55.3	24.9
	1100 F - 1 h	Vacuum	257.8	270.9	44	49.7	23.4
	1150 F - 1 h	Vacuum	227.9	227.9	1	7.7	24.1
	1150 F - 1 h	Air	194.0	194.0	11	8.8	24.7

*Total elongation in 1 inch

tensile properties is shown in Figure 2. It is apparent that for each condition of warm work there is a particular tempering treatment for an optimum combination of tensile properties.

The properties produced by warm extrusion and tempering are compared with those of warm-rolled material of the same nominal composition* in Figure 3. The properties are quite similar, with the extruded and tempered materials showing a slight superiority at high amounts of warm work. Examination of the points shown for the solutionized material (0% warm work) indicate that the differences at low amounts of warm work are most likely due to differences in the heats used for the extrusion and rolling studies.

Naturally, for a given set of warm-working conditions, the correct austenite stability could be obtained by adjustment of the original alloy composition; or for a given composition, the average working temperature could be adjusted to achieve the same end result. However, these are not always practical alternatives once a heat has been made or once the material has undergone thermomechanical treatment. It is an extremely encouraging result that difficulties in alloy composition control or processing temperature control can be compensated by a final heat treatment to adjust the austenite stability. It is important to note that the correction provided is only in the direction of decreased austenite stability. Conservative engineering practice might thus favor the high side of austenite stability in alloy design and processing control.

* AZRIN, M., and OLSON, G. B. Army Materials and Mechanics Research Center, unpublished research.

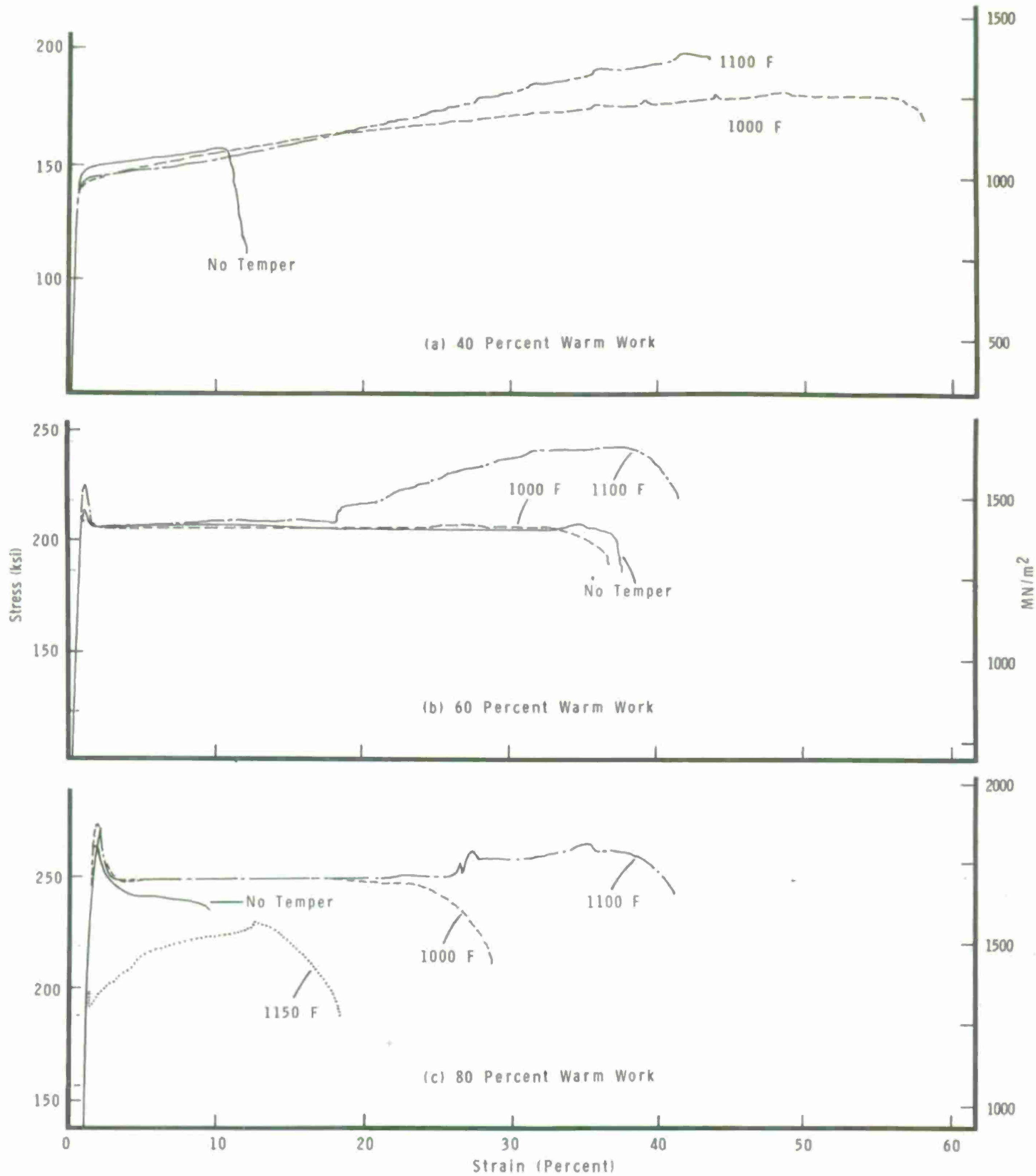

Figure 1. Effect of tempering temperature on the engineering stress-strain curves of warm-extruded TRIP steel.

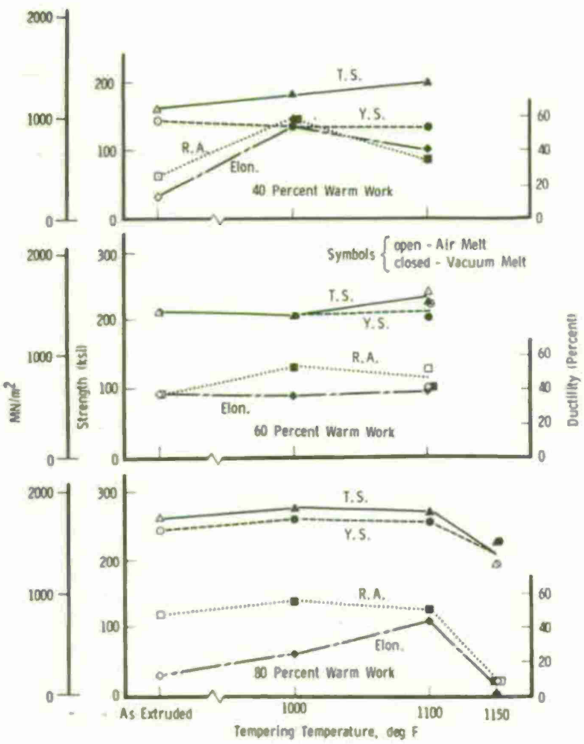

Figure 2. Effect of tempering temperature on tensile properties.

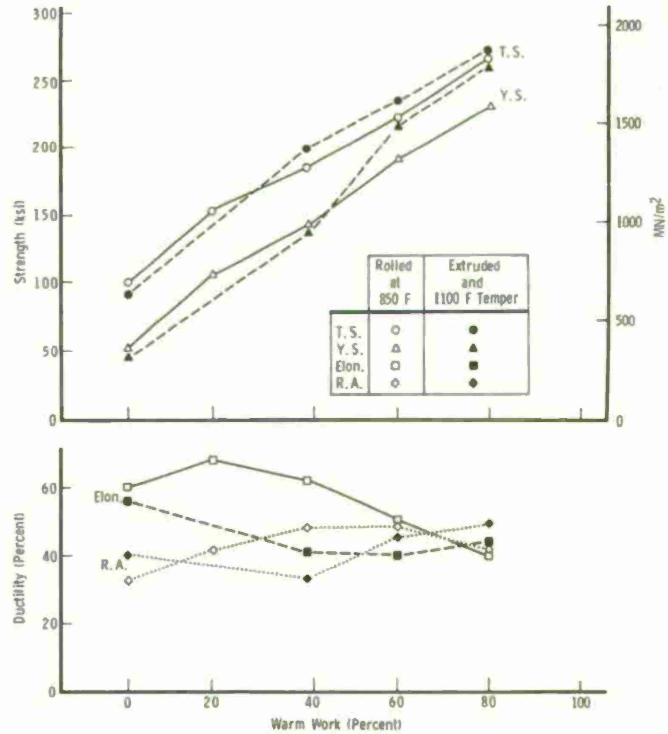

Figure 3. Comparison of tensile properties of rolled versus extruded TRIP steel.

CONCLUSIONS

The variation of the warm-working temperature has an important influence on the austenite stability and resulting mechanical properties of warm-extruded TRIP steel. High stability, due to a low average working temperature, can result in insufficient work hardening and lower ductility during room temperature service. Fortunately, the stability may be decreased by a simple heat treatment to give properties equivalent of superior to those obtained by warm rolling to equivalent reductions.

ACKNOWLEDGMENTS

The authors would like to thank Dr. R. Chait for his helpful assistance during the course of this work.

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